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Deterioration Monitoring on the School Fire, Pomeroy Ranger District: Second Year Post-Fire Season

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Pouch Fungus (*Cryptoporus volvatus*) conk on Fire-damaged Grand fir in a log deck on The School Fire, Pomeroy Ranger District, Umatilla National Forest.

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The enclosed Blue Mountains Pest Management Service Center report (No. BMPMSC-01-07) entitled, "Deterioration Monitoring on the School Fire, Pomeroy Ranger District: Second Year Post-Fire Season" evaluates causes and progress of deterioration in conifers in the second post-fire season after the School Fire. The report provides new information from the Blue Mountains on deterioration of conifers after fire from insects, pathogen-caused wood decay and stain, and weather.

We believe the report will be useful for documenting changes in wood quality after wildfire and in planning future fire salvage efforts.

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Please contact us if you have any questions regarding this report.

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Abstract

This study evaluates causes and progress of deterioration in fire-injured and fire-killed conifers in the second post-fire season after burning. Various amounts of fire damage occurred to conifers in the School Fire which burned approximately 28,000 acres on the Pomeroy Ranger District, Umatilla National Forest in August 2005. We conducted the study specifically to determine incidence of insect attack and the incidence and depth of sap rot in trees injured or killed by fire. We also determined the types of other agents of wood deterioration that occurred soon after the fire.

We examined decked logs harvested between late September 2006 and June 2007, and unharvested standing trees in partially burned stands. We examined logs in decks at three different locations to qualitatively determine if logs had been infested with insects and if other indicators of deterioration or defect were present (e.g., staining, sapwood decay, weather checking). We obtained tree mensuration data and deterioration measurements on live and dead trees 5-inches and larger in diameter (dbh) from variable-radius (BAF 20) sampling points established along random transects located in 3 different areas of lightly-burned to moderately-burned mixed-conifer stands within the boundary of the fire.

In addition to woodborer exit holes and beetle galleries that etch the surface of sapwood, blue staining of sapwood of the pine logs was the most readily recognized indicator of deterioration in log decks. Weather checks were also commonly observed in decked logs of all species but were less recognizable in standing fire injured trees. Standing grand firs, both dead and live, were the only species on our sample plots with observable weather checks.

Certain bark beetle and woodboring species were attracted to fire-scorched and fire-killed trees during and immediately after the wildfire passed through the forest. The colonization by some of these insects was almost immediate and signaled the beginning of the deterioration process. The initiation of stain and decay by fungi commenced when insects attacked the fire-killed or –injured trees and inoculated the sapwood with spores or mycelial fragments carried on their bodies.

Although it was not possible to determine by our sampling methods whether fire or insects had killed trees on sample points, nearly all of the measured plot trees has some degree of fire injuries to either roots, bole, or crown, and most had been attacked by insects by the second post-fire season. Mortality rate of Douglas-firs on plots was 15.4%, and grand firs had a mortality rate of 48.3%. It was clear that fire killed or weakened conifers of all species and predisposed them to attack by insects.

Using Spearman Rank-Order correlation analysis, we found a significant interdependent relationship between sap rot and insect infestation indicators in trees ($P = 0.07$), and a significant relationship between sap rot and trees infested with insects ($P = 0.05$). Indicators of infestation such as pouch fungus (*Cryptoporus volvatus*) conks, insect

boring dust, evidence of woodpecker feeding, insect entrance or exit holes, and sloughing bark with insect galleries beneath, can be used to help determine the "dying tree" status, but are more reliable when used in conjunction with other methods to assess post-fire tree survival.

Average depth of sap rot penetration varied by tree species and by live or dead status within a given species. Fire-killed grand fir exhibited the greatest depth of sap rot by the start of the second post-fire season with sapwood decayed to an average depth of 0.67 inches (SE = 0.15, η = 14), followed by live grand fir with sap rot penetrating to a depth of 0.40 inches (SE = 0.09, η = 15). We found a similar decay pattern in Douglas-fir with sapwood decay depth being greater in dead trees ($\bar{\chi}$ = 0.20, SE = 0.02, η = 4) than in live ($\bar{\chi}$ = 0.04, SE = 0.03, η = 22). We found the least penetration depth of sap rot in live ponderosa pines and western larches.

Sap rot penetration depth differed significantly between live and dead grand firs, $F(1, 6)$ 6.85, $\rho < 0.05$, and between live and dead Douglas-firs, $F(1, 6)$ 30.73, $\rho < 0.001$. There was no significant difference in sap rot depth among the cardinal sampling directions at the 0.05 level of significance within either the live or the dead tree status categories for either grand fir or Douglas-fir.

"Opinions" from the 9th Circuit Court of Appeals or by individuals that imply dying trees, for the purposes of post-fire salvage, cannot be considered "dead" because a tree with any amount of "life" in it, is still "live" and not "dead" based on the definition of "live" given by Webster's Dictionary, are biologically and scientifically flawed. Dying trees that meet certain physiological criteria (e.g., are damaged or attacked by insects and are expected to have a dead or nonfunctional root system or a nonfunctional stem within 5 years) may be considered either dead or in imminent danger of death based on the peer-reviewed scientific literature (see Filip et al. 2007). Most trees on our School Fire sample plots are in this category and showed clear signs of irreversibly progressive deterioration that will soon result in the cessation of life due to these trees having ongoing impairment of cambium and sapwood xylem function because of damages caused by infestation of insects and fungal pathogens. This study supports the "dead" tree definition as described in the foregoing and in the paper by Filip et al. (2007).

Deterioration of fire-injured and fire-killed trees caused by a variety of biotic and abiotic agents begins almost immediately after fire and progressively worsens with time until losses of wood volume eventually reach levels that renders trees unsalvable from an economic standpoint. If economic recovery is a goal of post-fire restoration projects, science-based guidelines to assess post-fire tree survival should be used to assist in tree salvage marking to target the removal of those trees with poor chance of survival; and salvage should begin as soon as possible, and conclude within 12 months after the fire to minimize merchantable volume losses and maximize recovery of sound wood volume. A decision to proceed with salvage should include a consideration of the trees' deterioration status as well as an evaluation of environmental conditions that might otherwise controvert proceeding if such assessments revealed that to do so would result in undesirable environmental effects, or be too costly to properly mitigate.

Contents

Letter of Transmittal i

Abstract ii

Contents iv

Introduction 1

Materials and Methods 4

- Log Decks 4
- Standing Trees 5

Results and Discussion 7

- Log Decks 7
- Standing Trees 14
  - *External Indicators of Insects Colonization* 16
  - *Susceptibility of Fire-Injured Trees to Insects* 16
  - *Insect and Sap Rot Interdependency* 19
  - *Sap Rot Penetration Depth* 21
  - *Volume Losses and Progression of Deterioration* 24
  - *Weathering* 26

Conclusions 28

Acknowledgements 30

Literature Cited 31

Deterioration Monitoring on the School Fire, Pomeroy Ranger District: Second Year Post–Fire Season[1]

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Introduction

Insect, pathogen, weather, and wood decay interactions in weakened, dying, and dead conifers are expected natural consequences of wildfires in the coniferous forests of interior western North America. Although wildfires commonly occur in eastern Washington and Oregon forests, Hadfield and Magelssen (1997) noted the paucity of available published information describing the deterioration of conifers in these forests after fire, especially as a result of the actions of insects and fungi. The recovery of usable wood products from dead and dying trees is an important economic aspect of most post-fire recovery projects. Information on the rates of insect attack of fire-injured or –killed conifers, the interactions of insects and pathogens in host-tree species associated with fire, and the deterioration rate of wood quality given these interactions, are factors affecting the merchantability of fire-affected trees and economic recovery of wood fiber after wildfire.

In their comprehensive report, Hadfield and Magelssen (2006) provide an excellent, detailed study of deterioration changes in 7 western conifer species followed for 5 years after wildfire. This study fills in a good portion of the existing information gap on post-fire deterioration of conifers in the eastern parts of Washington and Oregon. All 7 conifer species studied are those that occur in stands in the School Fire that burned

[1] Report No. BMPMSC-01-07, dated April 10, 2008.

approximately 51,000 acres in southeastern Washington in August 2005, including 28,000 acres on Pomeroy Ranger District of the Umatilla National Forest (USDA 2006). Hence, this study is particularly relevant to the School Fire, and provides a good backdrop and reference for projecting the future course of wood quality changes attributable to char, insect attack, fungal growth, and weather effects on fire-injured and –killed trees in this ecotype. The work by Hadfield and Magelssen (2006) is supplemented for some species by two other fire-related studies. The first is a review and synthesis of the literature on deterioration of fire-killed or fire-damaged timber in the Western United States by Lowell et al. (1992). The second important study is by Eglitis (2006), who examined the colonization of fire-damaged ponderosa pines by bark beetles, woodborers, and blue-staining fungi during the first year after wildfire. The Eglitis (2006) study provides valuable data on the appearance of early agents of wood deterioration in ponderosa pine.

Post-fire salvaging of dead and dying trees on the School Fire began in 2006. During the winter of 2006-2007, the Pomeroy Ranger District contacted the Blue Mountains Pest Management Service Center over concerns about insect infestations associated with logs that had been salvaged in the first round of post-fire salvaging on the School Fire and stored in log decks at landings over the winter. In addition, the Pomeroy District expressed concerns that insect populations might be increasing in dead or dying trees within the burned area and perhaps might spread to surviving trees within the fire perimeter, or to trees in the recent (2006) Columbia Complex Fire, lying adjacent to and mostly west of the School Fire. Concerns over these issues may not be unfounded given the tendency for insect population buildup in burned areas and associated deterioration of merchantable material from stain and decay fungi vectored by such insects. These processes could result in potential losses in ecological integrity of forests as well as in the economic returns from salvage of merchantable dead and dying timber. Also, fire-killed or fire-damaged trees are an increasing public safety issue along roads and highways experiencing wildfires (see FSM 7700; Toupin and Barger 2005).

Interactions among fire, insects, and pathogens in fire-adapted ecosystems in the Blue Mountains of southeastern Washington and northeastern Oregon have ecological and economical implications beyond post-fire restoration and recovery of wildfire areas. The effects on forest health of excluding fire from a fire-adapted landscape are well known from the published literature, and especially from the literature related to the Blue Mountains (Quigley 1992; Wickman 1992; Mutch et al. 1993; Johnson 1994). Other regions also supply many additional examples. In the Rocky Mountain region fire exclusion has produced uniformly old stands of lodgepole pine (*Pinus contorta*) that provide ideal conditions for continued survival and spread of mountain pine beetle, *Dendroctonus ponderosae* (Hagle and Schmitz 1993) and dwarf mistletoe (*Arceuthobium americanum*). Fire exclusion has enabled dense understory stands of Douglas-fir (*Pseudotsuga menziesii*) and grand fir (*Abies grandis*) to develop beneath old-growth Douglas-fir overstories. Ground fires no longer remove small trees that have become infected with dwarf mistletoes (*Arceuthobium* spp.), thus promoting spread of these and other diseases in such stands (Hagle and Schmitz 1993; Filip et al., 2007). The interactions of fire, insects, and pathogens in fire-adapted systems are also important

considerations in restoring natural fire cycles. For example, Parker et al. (2006) observed: "*A clear understanding of the relationship among fire, insects, and pathogens can help frame the costs and benefits of management practices designed to restore more natural fire cycles to these fire-adapted ecosystems.*" Under natural conditions, each agent alone, as well as the interactions of fire, insects, and pathogens, may enhance the long-term productivity of forests by functioning as natural thinning agents and accelerating nutrient cycling from decomposing trees (Filip and Showalter 1993; Filip et al. 2007). In the final analysis, interactions between fire, insects, diseases, and decay fungi can have multiple major consequences for post-fire economic recovery of merchantable timber, as well as affecting ecological processes, restoration of natural fire regimes, timber production, and forest productivity and management goals (Showalter and Filip 1993; McCullough et al. 1998; and Parker et al. 2006).

Of the assemblage of insects attracted to fire-injured or fire-killed trees in the years after a wildfire, bark beetles (Coleoptera: Curculionidae, Scolytinae) are of special concern because they commonly attack trees weakened, but not killed, by fire and sometimes build populations that then spread to less severely injured surviving trees, or uninjured trees in adjacent stands (Miller and Patterson 1927; Miller and Keen 1960; Stevens and Hall 1960; Furniss and Carolin 1977; Fischer 1980; Ryan and Reinhardt 1988; Amman and Ryan 1991; Rasmussen et al. 1996; McCullough et al. 1998; Bradley and Tueller, 2001; Conklin and Armstrong 2001; Fowler and Sieg 2004; Parker et al. 2006; Schwilk et al. 2006). Because bark beetles require fresh, succulent phloem and cambium tissues for brood development, they do not do well in the fermented, cooked, or dried phloem and cambium tissue of fire-killed trees (Hadfield and Magelssen 2006). Hence, bark beetles are typically found to be killers of fire-injured trees that otherwise would have survived. These insects could add considerable additional volume of wood fiber to the already dead and dying trees exposed to lethal temperature from the School Fire.

It has been our experience that fire-killed trees, while mostly avoided by bark beetles, are favored hosts for wood boring insects and wood wasps. Among the former, are members of the families Buprestidae and Cerambycidae, and among the latter, members of the family Siricidae, all of which are important causes of wood deterioration (Kimmey and Furniss 1943; Stevens and Hall 1960; McCullough et al. 1998; Parker et al. 2006).

Conversely, though it is unusual for bark beetles to attack dead trees, some have reported bark beetles attacking fire-killed trees, and this probably is due in part to the fact that the inner phloem and cambium are still acceptable for brood development. Eglitis (2006) reported finding infestation of fire-killed ponderosa pines by western pine beetle, *Dendroctonus brevicomis*, on the Hash Rock Fire in central Oregon. Hadfield and Magelssen (2006) also reported bark beetle attacks on fire-killed Douglas-fir, grand fir, lodgepole pine, ponderosa pine, and Engelmann spruce in several fires in eastern Washington that occurred in July and August of 1994.

Several woodborer species are "host generalists" and breed in a variety of conifer species. Others specialize only on certain conifers. Hence, damage from borers can be expected in practically all kinds of fire-killed trees (Stevens and Hall 1960). Borers not only will

attack dead trees, but also those that are partially killed by fire and bark beetles (Parker et al. 2006). Given this, we expected that woodborer damage already had occurred not only in various types of fire-killed conifers, but also in partially-killed trees on the School Fire, as well.

The purpose of this monitoring study was primarily to evaluate the condition of harvested trees in log decks, and unharvested, standing, fire-injured and fire-killed trees sampled two years after the fire to: (1) determine incidence of insect infestation; (2) determine the current amount of sapwood deterioration from stain and sap rot; and (3) determine incidence of checking in standing trees of different conifer species within the boundaries of the School Fire.

We hypothesized that the trees we examined in log decks on May 8-9, 2007—those harvested in the first round of salvage operations on the School Fire from late September 2006 through June 2007—would already have evidence of both bark beetle and woodborer infestation. We suspected they were already infested because these trees were still standing during part of the 2005 (after the fire) and the 2006 insect flight periods, and should have been attacked by insects during either of those seasons. We also surmised that the decked logs and unharvested standing trees would have measurable (or at least detectable) sapwood decay present if indeed they had been attacked by insects in either previous year.

The physical changes that take place in a tree following death by fire have been designated as "deterioration" by Kimmey and Furniss (1943). In this study, we expand upon their definition by including fire-injured as well as fire-killed trees, and redefine "wood deterioration" as changes in the quality or quantity of sapwood or heartwood fiber as a result of processes of weather checking, fungal staining, sap rot or heart rot, boring or larval mining by insects, and direct losses from fire charring.

Materials and Methods

Log Decks

We visited log decks at three different locations on the School Fire and visually examined logs in each deck to qualitatively determine if logs had been attacked by insects and if other indicators of deterioration were present (e.g., staining, sapwood decay, weather checking). We photographed logs that had infestation and decay indicators to document damage. We did not attempt to determine the depth or amount of sapwood decay because only a small amount of the surface of logs located at the top of the deck were accessible and this would not provide reliable estimates of deterioration.

We inspected log decks at these locations:

Stop ① – T.9N., R.42E., Sec. 3 and 10 (Stevens Ridge area)
Stop ② – T.9N., R.41E., Sec. 24 (area North of Willow Springs)
Stop ③ – T.9N., R.41E., Sec. 26 (area North of Willow Springs)

Standing Trees

We systematically established variable-radius plots (Basal Area Factor 20) along random transects located 2 or more chains from roads at 3 different areas in the stratum of lightly to moderately burned mixed-conifer stands to measure deterioration on unharvested standing fire-injured trees with green crowns. Our main criterion for selecting locations to establish plots was that fire not have killed or consumed all foliage in the tree crowns over most of the burned area to be evaluated. This was to insure that most trees within the variable-radius plot samples would be drawn from a population of trees that still contained live green crowns, or at least parts of the crowns still contained live green foliage, two years after the fire. We established as many variable-radius plots along each transect as allowed by the plot location selection criterion above, and terminated the transect when burn intensity increased to the degree that crowns no longer contained green foliage. We measured a total of 12 sampling plots and these exceeded the number needed to estimate mean basal area with a sampling error of 20 %. We measured the mean basal area on plots at 120 ± 20 ft^2/acre; Coefficient of Variation for basal area was 57.7.

Variable-radius plots systematically located along the sampling transects were separated by approximately 2-3 chains. We varied distances between plots when necessary to insure that each plot contained at least one or more trees. This systematic procedure assured that the plots would be located without bias toward selection of either plots or sample trees within plots. This point sampling procedure ensures that estimators such as basal area and other parameters are unbiased (Grosenbaugh 1955; Palley and Horwitz 1961).

We installed variable-radius plots along sampling transects at these locations:

Area ① – T.9N., R.42E., S½, NE¼, Sec. 6 (Abels Ridge area) – 2 transects, 4 and 1 plots
Area ② – T.9N., R.42E., N½, NE¼, Sec. 6 (Abels Ridge area) – 1 transect, 3 plots
Area ③ – T.9N., R.42E., NE¼, NW¼, Sec. 3 (Stevens Ridge area) – 1 transect, 4 plots

We sampled Areas ① and ② on May 8, 2007, and Area ③ on May 9, 2007.

At each variable-radius plot, we obtained measurements on all trees in the plot 5.0 inches dbh and larger regardless of species or size, whose diameters were large enough to subtend the fixed critical angle of the 20 BAF wedge prism.

We recorded each tree by species, diameter at breast height (dbh), whether it was alive[2] or dead, and signs of insect infestation. The infestation indicators were: presence of

[2] For purposes of this monitoring, we used the recent opinion of the 9th Circuit Court of Appeals, Case No. 06-35781 (D.C. No. CV-06-00229-LRS), dated February 12, 2007, regarding the definition of "live" for trees on the School Fire Salvage Recovery Project: "*The common understanding of the term 'live' is, quite simply, 'not dead…all the trees that have not yet died'*." In other words, for this monitoring study, we

pouch fungus (*Cryptoporus volvatus*) conks, insect boring dust (frass), evidence of woodpecker feeding (bark drilled or flaked away), insect entrance or exit holes, and sloughing bark with insect galleries beneath.

We verified insect infestations by determining insect species or guild present (e.g., woodborers, ambrosia beetles, etc.) based on removing small pieces of bark with a hand axe to expose galleries characteristic of each species or guild.

We recorded any fire injury to crowns, boles, and roots. We checked for root injury from fire on four sides of the tree by removing small pieces of bark from the upper portion of large roots or the root-crown regions with a hand axe, and observing whether cambium was live or dead on any of the quadrants. If one or more quadrants contained dead cambium, the tree was considered to have root damage from fire.

With the aid of a 10x hand lens, we measured and recorded presence or absence and depth of sap rot to the nearest 0.1 inch from all 4 cardinal directions at breast-height (4.5 ft. above the ground) on sapwood cores obtained from each cardinal direction with an increment borer.

Lastly, we recorded presence or absence of weather checking in the bole.

For the purpose of summarizing the data, we grouped all tree measurements by species, and by live or dead status. We computed binomial estimates of proportions for all presence or absence data included in the monitoring parameters measured or observed.

We used Analysis of Variance (ANOVA) to test for differences in sap rot depth measured from the four cardinal directions for each species by live or dead tree status. Because we sampled from both live and dead trees on our plots, we were interested in whether sap rot penetration depth differed between these groups; hence, we statistically compared sap rot penetration depths sampled at four cardinal directions around each tree (north, east, south, and west) for live and dead grand firs and live and dead Douglas-firs in a two-level mixed model nested Analysis of Variance (ANOVA) with equal sample sizes (Sokal and Rohlf 1995). We tested each species separately. We used this model to test these null hypotheses for both grand fir and Douglas-fir: (1) live and dead conifers (groups) have the same mean depth of sap rot penetration; and (2) cardinal direction sampling locations (subgroups) have the same mean depth of sap rot penetration. We used a nested model rather than a two-way ANOVA for our analysis because the difference in sap rot depth from any given quadrant could be due to random variation in the site of inoculation by sap rot fungi or by attack by insects that inoculate the sapwood with decay fungi. Our "group" attribute variable was live and dead, and our "subgroup" attribute variable, cardinal sampling location, was nested within groups since each value of this attribute variable was found in combination with only one value of the higher-level "group" attribute variable. Sap rot penetration depth was our measurement or observation within each subgroup.

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adopted the definition that "LIVE" trees have green needles remaining in the crown, and "DEAD" trees have no green needles remaining in the crown.

Results and Discussion

Log Decks

The log decks that we examined contained a mix of conifer species. We did not attempt a comprehensive tally of species, but the general impression was that probably 60-70 % of the logs in the decks were grand fir and Douglas-fir, with the majority being grand fir. Ponderosa pine and lodgepole pine, as well as other species, were occasionally noted. The species in the log decks, of course, varied by the composition of fire-killed species within the particular plant associations that were cut during the first round of post-fire salvage harvesting.

The most evident deterioration of wood in log decks was blue-staining of sapwood of the pines, and occasionally sapwood staining in other conifer species (Fig. 1). Sapwood stain is the most important form of deterioration in conifers the first year after a fire (Lowell et al. 1992). Most pines had sapwood staining, but staining is not uncommon in other species. All species of conifers are susceptible to sapwood stain, but differ in degree of susceptibility (Lowell et al. 1992). Hadfield and Magelssen (2006) noted that by the end of the first year, a high proportion of the western larch in their study had stain associated with, and almost certainly introduced by, woodborers.

Figure 1. Blue-stained pine in log deck on School Fire, May 8, 2007, Pomeroy Ranger District, Umatilla National Forest.

The bluish stain in sapwood is mostly caused by species of Ascomycete fungi belonging to the genus, *Ophiostoma*. These fungi are closely associated with bark beetles (Perry 1991; Harrington 1993; Paine et al. 1997; Six 2003). Although it is commonly known that bluestain is introduced into pines by bark beetles, sapwood staining in other conifer species may be due to woodborer infestations (Hadfield and Magelssen 2006). For example, among the various fungi Garcia and Morrell (1999) isolated from adults of a common woodborer, the golden buprestid, *Cypriacis* (=*Buprestis*) *aurulenta* (family Buprestidae), a species with a wide host range including grand fir, Douglas-fir, ponderosa pine, lodgepole pine, and several other pines as well as western redcedar in Washington and Oregon (Barr 1971), some were sapwood-inhabiting members of the genera *Trichoderma*, *Penicillium*, and *Alternaria*. *Alternaria* spp. are known to cause blue stain in sapwood of trees (Garcia and Morrell 1999). In addition, two species of *Alternaria* (*A. tenuisimum* and *A. diantha*) have also been isolated from another common woodborer species, *Buprestis langi* (Garcia et al. 1997). Larvae of *Buprestis langi* are known to bore in the wood of Douglas-fir (Barr 1971). Several woodboring beetles belonging to the family Cerambycidae also have been found to be associated with *Ophiostoma* species (Eglitis 2006). It is probable that many other woodborer species also vector sapwood-staining and decay fungi, but fungal isolation has been attempted from relatively few woodborer species to date.

Blue stain associated with bark beetles develops soon after infestation and spreads quickly through the ray parenchyma cells, sometimes involving a substantial proportion of the sapwood volume. Harvey (1979) reported that approximately 2 % of the sapwood volume of lodgepole pines killed by mountain pine beetles, *Dendroctonus ponderosae*, was bluestained after about a week; and, within 9.5 months of beetle attack, 28-65 % of the stem volume contained bluestained ray parenchyma tissue. Whitney (1971) found walls of egg galleries and associated frass (i.e., wood or bark boring dust and insect feces) of mountain pine beetle reared in bolts of lodgepole pine to be thoroughly colonized by abundant growth of blue-stain fungi and yeasts as early as three days after initiation of the egg gallery by adult female beetles.

Occurrence of the School Fire in early August 2005 likely did not preclude insect attack of some of the fire-injured trees in 2005 since new broods of western pine beetle, *Dendroctonus brevicomis*, develop and emerge in August, and as late as early October in some locations across its range (Keen 1928). This later emerging new generation of beetle adults attack trees during the fall. Pine engravers, *Ips pini*, can also attack trees in the fall during the third generation of brood; the generation which overwinters. In addition, various species of woodborers fly throughout the summer and well into the fall, initiating attacks on both fire-killed and fire-injured trees during this period. All these beetles are capable of vectoring stain fungi, so it appears likely that some trees were attacked by beetles and became inoculated with stain fungi the year of the School Fire. Many more trees were likely attacked in 2006 when overwintering beetles that became active that spring had the entire flight season to attack and inoculate trees with stain and decay fungi. The close association of blue-stain fungi with bark beetles and woodborers insures early colonization by staining in fire-injured or -killed conifers.

Amount of degrade of timber from blue stain can be high in trees killed by insects. Johnson (1940) reported that degrade in insect-killed ponderosa pine from blue stain amounted to as much as 50 % in trees containing advanced broods of *Dendroctonus*, *Ips*, and *Melanonphila* (a common woodborer in the family Buprestidae). Because blue stain fungi grow rapidly, this partially accounts for the large amount of degrade that occurs from this agency, especially in ponderosa pine. Eglitis (2006) reports in his study on fire-damaged ponderosa pines in central Oregon that insect-introduced stain developed in the sapwood at the rate of 10-50 mm per week. Hence, staining of the sapwood was well developed within a month after the insect vectors colonized the host tree with the *Ophiostoma* fungi.

The rapidity at which certain woodborers invade trees involved in a fire is remarkable considering that numbers are often drawn in over considerable distance. *Melanophila acuminata*, *M. consupta*, and other *Melanophila* species are attracted to pines still smoldering or burning in forest fires, as well as many other "heat" sources (Linsley 1943). These pyrophilous beetles fly to and alight on trees just after the flames subside and temperatures are tolerable by the beetles (Hart 1998). There they mate and lay eggs in the still smoldering bark. Attraction by these woodborers is due to their unique ability to detect infrared radiation from a fire and thereby locate and exploit breeding habitat before their competitors (Evans 1966).

Other insects that infest recent forest fire areas arrive weeks or sometimes months later. Nevertheless, there is a rapid succession of colonization by insects in fire-killed and fire-injured trees, and their role in post-fire deterioration of these trees begins almost immediately. The initiation of stain and decay by fungi introduced by these insects also commences at the time of these attacks, soon after the fire. It is the subsequent waves of woodboring and other insects, along with their associated microorganisms, the foraging for insects by woodpeckers, bears and other animals, and weathering processes, which eventually complete the decomposition of fire-killed trees.

Richmond and Lejeune (1945) reported that in the case of fire-killed white spruce in northern Saskatchewan, some woodborer species initiated attacks on trees the same season as fire occurrence. Hadfield and Magelssen (2006) also reported woodborer attacks the same year as fires in eastern Washington on Douglas-fir, western larch, ponderosa pines, and some grand firs after fires in eastern Washington. Eglitis (2006) observed red turpentine beetle (*Dendroctonus valens*) attacking scorched pines the same year and shortly following the Hash Rock Fire on the Ochoco National Forest in central Oregon in 2000, and speculated that because of the early flight of some woodborers that extends into fall, these insects probably infested some of the fire injured and killed trees soon after the fire in August.

The size of the available insect population determines to a large degree the amount of post-fire insect activity and associated deterioration in fire-killed and fire-injured trees (Kimmey and Furniss 1943). Recent burns, blowdown events, and other forest disturbances in the vicinity of a forested area that later burns in a wildfire contributes to a

localized buildup of insect numbers and increases the abundance and diversity of insect species that less commonly occur in the undisturbed forest prior to a fire. This insect population is then readily available to rapidly colonize injured or killed host trees in a fire nearby. Kimmey and Furniss (1943) observed a correlation between the amount of woodborer damage to heartwood of fire-killed Douglas firs, and nearness to old burns. It is not surprising, therefore, that an aggregation of various recent small-scale disturbance events, including smaller wildfires, prescribed fires, pile burning, blowdown, and other disturbances might contribute to a scattered, increased presence of beetles on the Pomeroy Ranger District, and a source of insects to attack host trees that became available on the School Fire. When these insect-infested host trees are soon salvaged and find their way into log decks, the extent of early deterioration caused by insects and fungi becomes apparent, as in the case of the decked logs in the School Fire.

On close inspection of logs in the School Fire decks, we found ample evidence of insect attack and degradation associated with bark beetle galleries (Figs. 2 and 3), woodborer exit holes and tunnels (Figs. 4 and 5, respectively), sapwood decay indicated by fungus fruiting bodies and stain (Fig. 6), and weather checking (Fig. 7).

Examination of logs in different log decks from several locations within the School Fire salvage units confirmed that bark beetles and woodborers attacked trees just after the fire, prior to salvage cutting. Insects introduced various stain and decay organisms into the standing trees at the time of their attacks. Evidence of these agents is easily identified in the decked logs (see Figures 1-7). These observations correspond with evidence presented by Hadfield and Magelssen (2006), that wood changes due to agents of deterioration occur soon after trees are killed by fire; some almost immediately after the burn. Staining of sapwood by insect-introduced stain fungi was common in nearly all species of conifers on the School Fire. Anytime insects are involved, stain is a significant form of degrade. It has been noted by Johnson (1940), Wright and Wright (1954), and Wickman (1965) that sapwood stain which is introduced by bark beetles and woodborers

Figure 2. Pine engraver galleries in ponderosa pine.

Figure 3. Fir engraver galleries in grand fir.

Figure 4. Woodborer exit holes.

Figure 5. Woodborer gallery on cut end of log.

Figure 6. Pouch fungus conk indicates the presence of *Cryptoporus volvatus*, which causes gray sap rot.

Figure 7. Weather checking and woodborer galleries.

is by far the most important cause of degrade in trees killed by insects and in insect-attacked windthrown trees.

The rate of other wood deterioration changes due to other agents was more variable, depending on tree species.

From the perspective of wood utilization possibilities, decay of sapwood may only involve a small portion of the entire sapwood area if a fire-killed tree is salvaged soon after the fire (Fig. 8). However, as deterioration advances, the costs of raw product recovery and milling progressively increase, and net production decreases because of increased breakage during harvest and need for heavy slabbing and handling costs during milling to recover products from deteriorated logs (Beal et al. 1935; Parry et al. 1996). Wright and Wright (1954) observe that insect-caused losses in fire-killed timber progresses from sapwood to heartwood as woodborers extend their galleries into the heartwood with passage of time, thereby increasing the amount of deterioration that occurs in trees killed by fire. They conclude that borers can be expected to become increasingly important as agents of deterioration as time passes. The holes produced by insect borers, along with sapwood decay, stains, and weather checks ultimately result in product degrade and loss in product volume and value.

Although we observed many woodborer galleries in the decked logs (Figs. 4, 5, and 7), we made no attempt to quantify the borer holes or measure the depth of tunnels in the sapwood or heartwood. However, woodborers represent a significant agent of wood deterioration either directly by the creation of "wormholes" or indirectly by facilitating or predisposing fire-injured and fire-killed trees to other wood-deteriorating agents including wood-decay fungi and woodpeckers that forage for insects within infested trees.

Figure 8. Rapid salvage insured that incipient sap rot in this log occupied a relatively small amount of the total sapwood volume.

Few have attempted to quantify the amount of sapwood and heartwood destroyed by the tunneling of woodborer larvae. The tortuously-winding galleries of woodboring beetles and wood wasps represent a cumulative unknown and difficult to measure volume of tunneled wood. Yet, in a few cases, authors have provided gross estimates of the decrease in volume recoverable from woodborer-infested trees. Wilson (1962) notes that up to 5 % decrease in wood volume may result from borings in heavily infested "pulpstick" of various eastern conifer species by the white-spotted sawyer, *Monochamus scutellatus*, and the deep tunnels and discoloration caused by associated fungi may reduce the value of lumber that can be manufactured from infested logs by as much as 35 %. The larval stage of this cerambycid beetle is one of the most serious woodborers in fire-scorched, injured, dying and recently-felled spruce, pines, Douglas-fir, and true firs (Furniss and Carolin 1977).

Prentice and Campbell (1959) reported that volume losses seldom exceeded 1.5 % in sample logs of Jack pine and black spruce pulpwood after one year of woodborer surface feeding and tunneling in Manitoba, Canada. However, for woodborer species that take more than one year to develop, it is probable that volume losses would be much greater.

Richmond and Lejeune (1945) measured *Monochamus* spp. galleries in white spruce after a fire in northern Saskatchewan, Canada that penetrated into the heartwood in a U-shaped pattern that may extend as much as 7 inches or greater in length; and deterioration losses due to these galleries resulted in output of lower average grade of lumber. They report that mill runs with borer-infested trees averaged 50 % No. 3 or better grade lumber, whereas, normal grades in green timber yields an average of 60 % No. 3 or better.

While it is difficult to estimate the actual amount of deterioration caused by woodboring beetles, it is clear that their influence on the quality and quantity of commercially usable wood fiber available from salvaged fire-injured or fire-killed trees is negative from an economic perspective. Deterioration from this agenct begins almost immediately after trees are injured or killed, and is progressive over time. Interactions with other agents such as stain and decay fungi, and woodpeckers, only serve to accelerate the deterioration process and reduce even furter the economic value of trees salvaged after fire.

Woodpeckers are commonly active in burned areas and were present after the School Fire, but probably not at high population levels. Although we were not specifically looking for evidence of woodpecker foraging on decked logs, undoubtedly, there was some present. Nevertheless, woodpeckers foraging for bark beetle and woodborer grubs in fire-injured or –killed trees also cause a largely unknown amount of damage and wood volume loss in trees in the months succeeding a fire. In their search for insect prey, foraging birds (particularly woodpeckers of the genus *Picoides*) puncture the bark and fragment the underlying sapwood, altering the structure and microhabitat in localized areas of a snag, and facilitating the inoculation into the sapwood region of filamentous decay fungi and yeasts carried on their bills (Farris et al. 2004). In addition to the obvious physical damage to the outer cylinder of wood from woodpecker foraging, the authors note that results of their study suggest a possible link between bark and woodboring beetle colonization, woodpecker foraging activity, and phloem and sapwood decomposition in ponderosa pine.

It has been long speculated that woodpecker feeding behaviors that open the bark and mechanically degrade the sapwood may provide infection courts for airborne spores or create microhabitat conditions favorable for wood-decaying organisms (Otvos 1979; Ostry and Anderson 1998) [cited in Farris et al. 2004]. The actual recovery of numerous organisms from the bills of woodpeckers by Farris et al. (2004) may suggest that foraging woodpeckers aid in the dispersal of decay organisms that may promote the decay of ponderosa pine snags, and perhaps other conifers.

An alternate view of the role of woodpeckers is in controlling or limiting woodborer-caused damage by removing shallow-tunneling larvae during woodpecker foraging

activities. Early foraging by woodpeckers may reduce woodborer-caused deterioration by preventing the insects from tunneling deeply into the heartwood. However, some authors have suggested that the woodpecker's role as predator may be limited. Parmelee (1941) observed that in the Presque Isle Fire area in Michigan, woodpeckers were fairly numerous, but their prevention of much damage by removing woodboring insects—though important—was questionable. Buttrick (1912), offered the opinion that generally birds function in keeping down the numbers of insect pests rather than in saving timber already infested, since by the time the borers had tunneled 2 or 3 inches into the wood, only the larger woodpeckers can reach them, and then only when the wood is partly decayed.

Standing Trees

Within the dataset we obtained from the 12 variable-radius plots established in different areas of the School Fire, we collected information on a total of 73 trees: 16 ponderosa pines, 2 western larches, 26 Douglas-firs, and 29 grand firs.

We recorded the status of trees in our dataset as live or dead. Earlier, we defined "live" trees in accordance with a recent opinion of the 9th Circuit Court of Appeals regarding the School Fire Salvage Recovery Project, Case No. 06-35781 (D.C. No. CV-06-00229-LRS), dated February 12, 2007, which required the defining of any tree with any live (green) needles as a "live" tree. While procedures that assess tree survival after wildfire, such as those proposed by Scott et al. (2002), and some published literature (e.g., Filip et al. 2007), would disagree with that definition, the present study adopted the court's definition, in part, to determine whether this definition of a "live" tree is adequate to describe a healthy tree that has survived fire and will remain alive in "healthy" condition for some time into the future. This definition would require that trees such as the one shown in Figure 9 remain unsalvaged, even though this tree clearly lacks an adequate crown to maintain a photosynthetic rate high enough to keep the tree alive in future years.

In addition, our examination of this tree (Fig. 9.) on a variable-radius plot found it to be infected with Douglas-fir dwarf mistletoe (*Arceuthobium douglasii*), a pathogen of Douglas-fir that debilitates its hosts and predisposes severely-infected individuals to infestation by Douglas-fir beetle (*Dendroctonus pseudotsugae*) and woodborers (Fig. 10). It also was found to contain incipient sap rot that already had penetrated to a depth of 0.3 in. into the outer sapwood. For all intents and purposes, this tree could be declared "dead" based on technical points discussed in Filip et al. (2007).

The dataset was aggregated by species and live or dead status for statistical testing and in order to calculate the binomial estimates of the proportions of trees within these aggregates for various parameters (Table 1).

Figure 9. "Live" Douglas-fir infected with dwarf mistletoe on plot 2, area 1 of School Fire monitoring plots.

Figure 10. Douglas-fir beetle and woodborer galleries in "live" dwarf mistletoe infected Douglas-fir shown in previous figure.

External Indicators of Insects Colonization

We found good correlation between proportions of trees with insect infestation indicators and the proportion of trees actually colonized by insects for both live and dead trees (Table 1). Hence, the Supplemental Criteria to assess trees with "Moderate Probability to Survive" in the Implementation/Marking Guides for the School Fire Salvage Recovery Project (see USDA 2007, Appendix B), which are the same criteria we used for this monitoring effort, appears to reliably identify trees with actual infestation by insects. In no cases did the indicators overestimate actual proportion of trees with insect infestation as verified by successful larval galleries and/or presence of insect stages within the tree; and in only a few cases involving live and dead Douglas-fir and live grand fir, did the indicators underestimate actual proportion of trees that had been infested. In the latter cases, we found evidence of insect colonization in the absence of visible external indicators.

Susceptibility of Fire Injured Trees to Insects

Nearly all plot trees exhibited some measure of fire damage to their crown, bole, or roots (Table 1). Our plots were established in areas of the fire where trees were underburned at different intensities, and many trees appeared to have survived as indicated by at least some green needles remaining in their crowns. As a consequence of the unequal and patchy damage to the crowns, boles, or roots of these trees, a number were attractive to insects that initiated attacks on the boles and successfully established broods. Although we found no dead ponderosa pines or western larches on our plots, a small portion of the live trees of both these species were sub-lethally attacked by bark beetles or woodborers. However, pines and larches were least attacked of any species on our plots. Hadfield and Magelssen (2006) reported that in fire-killed trees in their eastern Washington study, all tree species were infested by woodborers, but thick bark species had more attacks than thin bark species. They reported large populations of woodborers in western larch at the end of the first year, and populations continued to be high each year through post-fire year 5. In their study, western larches were more severely infested by woodborers than the other species.

The numbers of trees within our variable-radius plots were adequate for evaluating several aspects of wood quality changes due to various agents of deterioration; but, because there were only 2 western larches on our plots, even though woodborers had initiated sub-lethal attacks on one, the sample size was too small to draw any meaningful conclusions. Hence, we omitted western larches from our analyses.

The proportion of live Douglas-firs attacked by insects was nearly twice that of live ponderosa pines; but, the proportion of live grand firs attacked was over four times as high as the pines (Table 1). All dead Douglas-firs and grand firs had been attacked by insects, but it was not possible to determine how many had actually been killed by insects by the second season after the fire (Table 1). The mortality rate of fire-injured Douglas-firs and grand firs on our variable-radius sample plots were 15.4 and 48.3 %,

respectively, by the beginning of the second post-fire season (Table 1). It is clear that fire played a role in weakening a portion of the trees of all species present on the School Fire and predisposed them to insect infestation.

Table 1. Binomial Estimates of Proportions of Various Monitoring Parameters from Conifers on the School Fire in the 2nd Post-Fire Year During May 8-9, 2007.

Species	Sample Size	Mean Diameter ±SE (in.)	Tree Status	Proportion with Infestation Indicators	Proportion with Insects Present	Proportion with Fire Injury			Proportion With Sap rot	Proportion Weather-Checked	Proportion with Dwarf Mistletoe
						Crown	Bole	Roots			
Ponderosa Pine	16	16.9±1.2	Live	0.1875	0.1875	0.5625	0.9375	0.6250	0.0625	0.0	0.0
Western Larch	2	14±0.1	Live	0.5000	0.500	0.5000	1.0	0.5000	0.0	0.0	0.0
Douglas-fir	22	18.4±0.9	Live	0.3182	0.3636	0.8182	1.0	0.6364	0.1818	0.0	0.1364
Douglas-fir	4	8.5±2.3	Dead	0.7500	1.0	1.0	1.0	1.0	1.0	0.0	0.7500
Grand Fir	15	16.7±1.3	Live	0.600	0.8000	1.0	1.0	0.9333	0.7333	0.0667	n/a
Grand Fir	14	13.4±1.9	Dead	1.0	1.0	1.0	1.0	1.0	0.9286	0.2143	n/a

Furthermore, the fact that variable numbers of trees of all species exhibiting green crowns during this evaluation have been colonized by insects to some degree, suggests that as the tree further weakens, future insect-caused delayed tree mortality can be expected. However, not all insect attacks may be lethal, and based on the data we collected, we cannot determine the proportion that might be expected to die as a result of some of these attacks. This would require a more comprehensive assessment of fire injury to the crown, bole, and roots in addition to other assessment factors, than what we obtained during this monitoring study. Evaluating trees with a post-fire tree survival rating system such as the one by Scott et al. (2002) that is being used for salvage marking on the School Fire (USDA 2006, 2007) would enable the classification of fire-injured trees into one of three potential survival classes: low, moderate, and high. The proportions of trees expected to die—those with low probability of survival—could then be calculated from these data.

Insect and Sap Rot Interdependency

Not surprisingly, we found the proportion of trees with sap rot present was strongly and positively correlated with both insect indicators and actual insect infestation (Tables 2 and 3, respectively) using the Spearman rank correlation. The correlation coefficient for insect indicators versus sap rot was significant at $P = 0.07$, and the coefficient for insect infestation versus sap rot was significant at $P = 0.05$. We calculated this nonparametric statistic because we lacked a sufficiently large dataset to determine whether the two variables were distributed as bivariate normal variables; a requirement of the Pearson Product-Moment correlation parametric test (Zar 1999). Results of the correlation tests indicate the proportion of trees with sap rot, and either insect indicators or actual insect infestation, varied interdependently.

Bark beetles and other insects are reported to acquire and disseminate spores and mycelial fragments of various wood stains and decay fungi; however, the fungi are not dependent on the insects alone for dissemination (Hadfield and Magellsen 2006; Harrington 1993). Although a close correlation often exists between these variables (i.e., bark- and wood-inhabiting insects and sap rot) it is impossible to determine or assume that one is the cause of the other, given our limited dataset. Hence, we carried out this statistical analysis only to prove the degree of association between the variables (i.e., statistical interdependence).

Studies have shown that deterioration of fire-killed true firs and other conifer species begins soon after the occurrence of fire, and is especially rapid among the smaller tree diameters. Lowell and Cahill (1996) reported a 5 % mean cubic volume loss within one year of all sizes of true firs being killed by fire in coastal forests in Oregon and California, primarily from weather checking, but sap rot introduced by beetles also played a role.

Decay of the sapwood by sap rot fungi was clearly an important progressive form of deterioration in their study that worsens with time. By the third year of this study, volume loss due to weather checking was found to be very high in Douglas-fir, ponderosa pine, and true fir, but was exceeded by sap rot resulting in significant culling of logs from

fire-killed trees. Regardless of conifer species, insects may initiate much of this deterioration both in trees killed outright by fire, and in trees that are injured and initially survive the fire (Eglitis 2006; Hadfield and Magelssen 2006).

Table 2. Correlation analysis of proportion of trees having sap rot with proportion of trees having insect indicators.

Spearman Rank-Order Correlation Analysis Results

Indicators vs. Sap rot:

Column Name	Insects	Sap rot
Sample Size	6	6
Minimum Sample Size		6
Sum Squared Difference of Ranks		8.000000
Standard Deviation		-1.724967
Significance Level of Std. Dev.		0.084533
Spearman's Rank Correlation		0.771429
Probability		0.072397

Table 3. Correlation analysis of proportion of trees having sap rot with proportion of trees having actual insects present.

Spearman Rank-Order Correlation Analysis Results

Insects vs. Sap rot:

Column Name	Insects	Sap rot
Sample Size	6	6
Minimum Sample Size		6
Sum Squared Difference of Ranks		6.500000
Standard Deviation		-1.814970
Significance Level of Std. Dev.		0.069528
Spearman's Rank Correlation		0.811679
Probability		0.049858

Hadfield and Magelssen (2006) observed that woodborers initiated several other changes in wood quality besides the physical effects of larval feeding on phloem and cambium tissues, and tunneling through the xylem. The loosening of bark during larval feeding at the bark-wood interface resulted in the development of cracks in the sapwood, staining of the sapwood also was common, and larval tunneling in the sapwood created foci for wood decay. They also noted that a high percentage of fire-killed Douglas-firs contained conks of *Cryptoporus volvatus*, the sapwood decay fungus causing gray sap rot that is vectored by Douglas-fir beetles (Borden and McClaren 1970; Castello et al. 1976). Associations of sap rot and other decay with beetle attack are known for other insect-

conifer host relationships, as well (Kim et al. 2005; Hadfield and Magelssen 2006; Parker et al. 2006).

Sap Rot Penetration Depth

The timing of occurrence and advance of decay in trees killed by fire are important considerations as they affect tree hazard, the feasibility of salvage, volume recovery, and utilization of merchantable wood fiber. Upon the death of a tree, sapwood becomes exceedingly susceptible to sap-staining and sap-rotting organisms like the pouch fungus (Basham 1958). Once stain and decay fungi are introduced into the boles of conifers by insects or through some other route, the infection of sapwood begins, and as a rule, the fungi advance through the wood until almost all of the tree is colonized (Basham 1958).

In the case of sap rot, the penetration of the fungi and associated decay depends on various factors and conditions. In some cases, the sap rot may rapidly develop to significant depth, while in other situations it may take several years for appreciable sap rot penetration to occur. Average depth of sap rot penetration on our School Fire plots appeared to vary both by species, and by live or dead tree status within species (Fig.11).

We found that the greatest depth of sap rot penetration occurred in dead grand fir ($\overline{\chi}$ = 0.67 inches, SE = 0.15, η = 14)), followed by live grand fir ($\overline{\chi}$ = 0.40 inches, SE = 0.09, η = 15). We observed a similar pattern in dead and live Douglas-fir, but with lower penetration depths, overall (Fig. 11). Sapwood decay depth in dead Douglas-fir averaged 0.20 inches (SE = 0.02, η = 4), and the decay depth in live Douglas-firs was 0.04 inches (SE = 0.03, η = 22). Live ponderosa pine and live western larch had the least amount of sap rot penetration by early in the second season after the fire. We did not have any dead ponderosa pines or western larches in our sample dataset with which to compare the depth of sap rot penetration with the live trees of these species; hence, the question of whether the sap rot penetration depth trends observed between live and dead grand firs and Douglas-firs hold for pines and larches on the School Fire remains unresolved at the current time. However, it is interesting to note that Hadfield and Magelssen (2006) reported that fire-killed ponderosa pines decayed more rapidly and thoroughly than the other conifer species they studied. Rapid sapwood decay in fire-killed ponderosa pines is likely due to a high ratio of sapwood to heartwood and thick bark that slows drying. The latter helps maintain for a longer time a more favorable microhabitat for fungal development compared to most other species.

Basham (1958) observed that the inherent moist conditions and relative lack of growth-inhibiting extractive substances provide dead sapwood with a more favorable environment than heartwood for the growth and establishment of fungi. We wonder to what degree other interspecific differences in conifers might account for differences in rate of sapwood penetration by sap rot fungi, but few studies address this issue. Beal et al. (1935) observed that rate of deterioration depends on the size of tree, position of log in tree, amount of sapwood, rate of growth, and environmental conditions. Kimmey and Furniss (1943) reached similar conclusions for fire-killed Douglas-fir.

In studies that measured the radial depth of penetration of visible deterioration of jack pine, red pine, and white pine for up to 5 years after being killed by fire in the Mississagi region of Ontario, Basham (1958) found that deterioration was greatest in those trees with widely spaced annual rings in the outer bole, and least in those with narrowly spaced rings. Kimmey and Furniss (1943) found a similar relationship in their study of fire-killed Douglas-fir.

We did not take particular note of the growth rate (width of annual rings) of the various conifer species on our plots. However, because grand fir typically has a relatively good rate of diameter growth and tends to have greater periodic annual increment (PAI) than other associated species (Hall 1981), and given the results shown in Figure 11, these appear to support Basham's (1958) finding for eastern pines, that trees with wider growth rings have greater deterioration rates and sap rot penetration depths than trees with narrower growth rings. Basham (1958) explains that the lower depth of sap rot penetration in trees with narrowly spaced growth rings is due to differences in the number and thickness of cell walls that must be penetrated in slow-growing wood in comparison with the reduced number and thickness of those encountered over a similar radial distance in fast-growing wood.

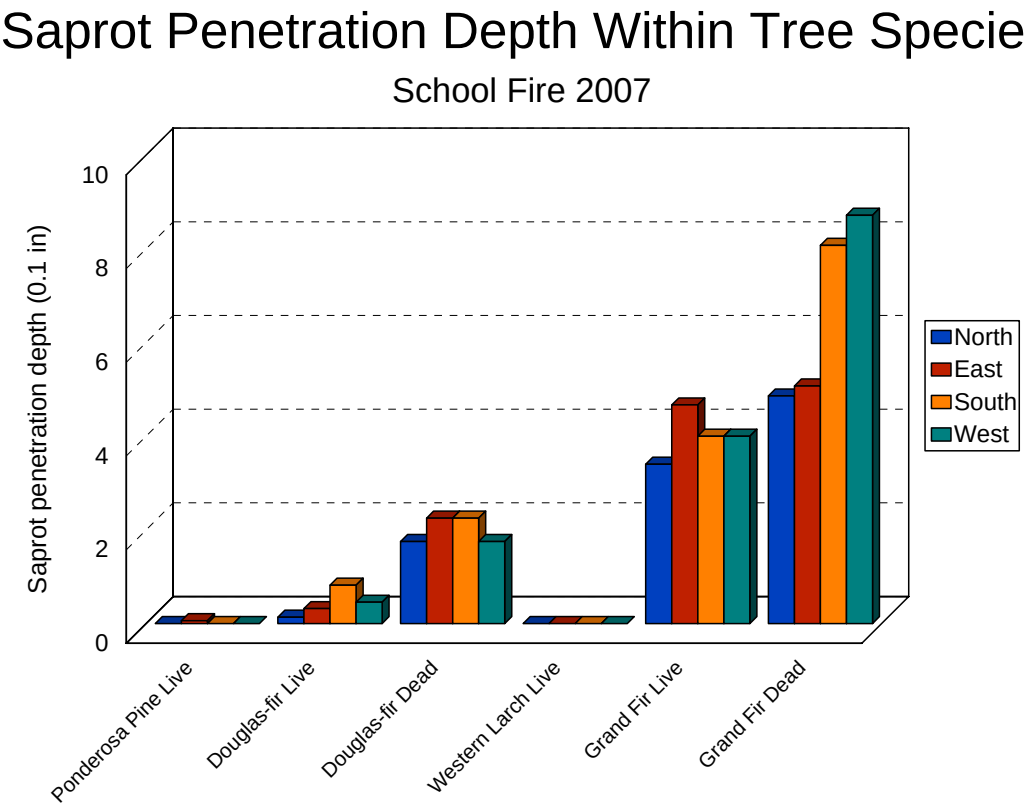

Figure 11. Variation in average sap rot penetration depth by species, live or dead tree status, and cardinal sampling location on the School Fire, Pomeroy Ranger District, Umatilla National Forest.

The result of our analysis for grand fir is given in Table 4. It can be seen that the test statistic, $F_s(1,6) = 6.85$, indicates that the variation between groups is high relative to the variation among subgroups within groups ($p < 0.05$), and hence, unlikely to occur by chance. Therefore, the mean sap rot penetration depths between live and dead grand firs are not equal, and we reject our null hypothesis that the means are equal.

The second test statistic, $F_s(1,108) = 0.55$, for the subgroups within groups (Table 4) indicates that the average variance of subgroup means within each group is low relative to the average variation among individual measurements within each subgroup ($p > 0.05$). Therefore, we determined there was no added variance among the cardinal sampling locations, and accept the null hypothesis that the subgroup means are equal.

We found similar results to those for grand fir when we tested Douglas-fir (Table 5). However, in Douglas-fir we found an even more significant variance component in mean sap rot penetration depth between live and dead Douglas-fir trees than we found between live and dead grand firs. We found the test statistic, $F_s(1,6) = 30.73$, between live and dead Douglas-firs to be very highly significant indeed ($p < 0.001$).
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Table 4. Analysis of Sap Rot Penetration Depth Between Live and Dead Grand Fir on Variable-Radius Plots in the 2nd Post-Fire Year of the School Fire on May 8-9, 2007.

	Sum of Squares	d.f.	Mean Square	Fs	P
Between Groups	205.2	1	205.2	6.85	0.040
Subgroups Within Groups	179.8	6	30.0	0.55	0.769
Within Subgroups	5891.4	108	54.5		
Total	6276.4	115			

Table 5. Analysis of Sap Rot Penetration Depth Between Live and Dead Douglas-fir on Variable-Radius Plots in the 2nd Post-Fire Year of the School Fire on May 8-9, 2007.

	Sum of Squares	d.f.	Mean Square	Fs	P
Between Groups	33.3	1	33.3	30.73	0.001
Subgroups Within Groups	6.5	6	1.1	0.35	0.910
Within Subgroups	299.1	96	3.1		
Total	338.9	103			

Few published post-fire deterioration studies report deterioration data in terms of average depth of radial penetration of sap rot. We found the reports by Beal et al. (1935), Kimmey and Furniss (1943), and Basham (1958) contain some data described in this format, but most publications report on volume losses, or the rate of volume loss of sapwood or heartwood, rather than provide specific measures of sap rot penetration, making comparisons difficult

Most studies suggest that trees with relatively thick sapwood deteriorate more rapidly than those with thin sapwood, and this explains, in part, why large, old trees, having proportionately thinner sapwood, deteriorate more slowly than faster growing, younger trees (Beal et al. 1935; Kimmey and Furniss 1943; Kimmey 1955; Basham 1958; Lowell et al. 1992). In addition, the large, old trees often have a band of tight growth rings that slow the penetration and advance of decay fungi, as noted above; whereas, younger, faster growing trees have wider growth rings that facilitate more rapid penetration by fungi and a faster rate of advance in the decay column.

Our deterioration monitoring data from the second post-fire year on the School Fire lacked any distinguishable trend or relationship in depth of sapwood decay relative to individual tree diameter. We found no significant correlations in any of the conifer species, live or dead, which provided reliable evidence that depth of sap rot penetration and tree diameter, co-vary or vary interdependently. Perhaps the reason for lack of correlation of these variables in our dataset is that the numbers of trees for any given species group or live or dead subgroup within the groups was simply too small to detect interdependency in our data. A larger sample size might better represent all tree sizes in numbers necessary to detect trends similar to what others have reported.

Volume Losses and Progression of Deterioration

Although we made no attempt to estimate volume losses due to various causes of deterioration of fire-injured and –killed conifers on the School Fire, others have conducted detailed studies of post-fire volume losses for various conifer species on other fires.

During the first year after the fires in eastern Washington in the summer of 1994, Hadfield and Magelssen (2006) reported finding little wood volume loss from decay, noting that others had reported this pattern, as well (cf. Basham 1957; Beal et al. 1935; Kimmey and Furniss 1943; Kimmey 1955; Lowell and Cahill 1996; Lyon 1977; Wallis et al. 1974). Hadfield and Magelssen (2006) observed that decay fungi, especially those associated with bark beetles, invaded fire-killed trees the year of the fire as indicated by presence of pouch fungus conks that appeared on ponderosa pines and grand firs at the end of post-fire year one. In general, pouch fungus conks first appear within 12-24 months after trees are killed by bark beetles (Scharpf 1993; Allen et al. 1996; Parry et al. 1996; Goheen and Willhite 2006). The first appearance of these conks indicates the early stages of sapwood deterioration. Allen et al. (1996) observed that although gray sap rot, the decay caused by the pouch fungus, is reported from a wide range of conifer hosts, it is most common in bark beetle- and fire-killed Douglas-fir. Hadfield and Magelssen (2006)

reported large numbers of Douglas-firs, ponderosa pines, and grand firs with pouch fungus conks at the end of the second post-fire year. Not only were cubic volume losses (based on gross volume of logs calculated by Smalian's formula) from pouch fungus-caused sapwood decay low the first year, the volume of wood affected by decay only increased slightly in year 2 and 3, and was still relatively low overall after 3 years.

Lowell and Cahill (1996) observed cubic volume losses of about 1 % for Douglas-fir and ponderosa pine, and 5 % for grand fir and white fir one year after trees were killed by fire in the coastal mountains of southern Oregon and northern California. By the second year after tree death, the occurrence of sap rot increased dramatically, affecting 44 % of the logs, but like the Hadfield and Magelssen (2006) study, they found volume loss due to this defect to be minor.

Although not involved in fire, the deterioration and lumber recovery study by Parry et al. (1996) of beetle-killed Douglas-fir and grand fir in the Blue Mountains of eastern Oregon provide additional local insight into the effects of time since tree death on volume loss, and wood product recovery and value. The authors of this study measured volume losses due to sap rot of 1.0, 8.1, and 11.4 % in Douglas-firs killed by bark beetles 2, 3, and 4 years earlier, respectively. For grand fir, they reported 1.7 and 8.0 % loss in volume by sap rot in trees killed by bark beetles 3 and 4 years earlier, respectively. The increases in sap rot over time for Douglas-fir and grand fir were statistically significant at $p=0.0001$ and $p=0.0003$, respectively, with years dead.

Perhaps a more generalized way of characterizing the potential volume losses and progression of deterioration of fire-killed timber is to simply quote this summary by Lowell et al. (1992):

> *"Blue stain will appear in susceptible trees within the first year. By the second year, some of the sapwood will be decayed. After 3 years, the sapwood of most softwoods has deteriorated beyond use (Kimmey 1955). This represents a greater volume loss for those species with a thick sapwood such as pines. By the fourth year after the fire, the rate of volume loss remains fairly constant from year to year. This means the radial distance the decay penetrates must increase each year (Kimmey 1955). Depth of decay is not identical at all levels in a tree and decay is not always continuous around the circumference. Trees with thick sapwood may develop pockets of rot. Even though volume recovery may be maximized by salvaging the small, young-growth stands first, value recovery may be greater by salvaging the mature stands first (Aho and Cahill 1984)."*

There are dangers in making generalizations since some may assume they apply to all situations. Although the quotation above states that after 3 years, the sapwood of most softwoods has deteriorated beyond use (Kimmey 1955), we take exception with that statement as there are some situations in which thin-barked species may dry out quickly after being killed by fire or bark beetles (Parry et al. 1996), making them less suitable for sap-rotting fungi to become established and grow. The situation with lodgepole pine is a

good example. In situations where lodgepole pine grows in an overstocked condition, the suppressed trees typically are maintained in pole or small sawlog size. When these stands are swept by fire, the thin bark often pops off the tree in the intense heat, and the wood dries out quickly, often becoming casehardened. The sapwood lacks a moisture content needed to support fungal growth. In these situations, a greater proportion of the sapwood may remain sound for a longer period of time; hence, extending the time of salvage for merchantable recovery.

Weathering

The influence of weather on the deterioration of fire-killed or fire-injured conifers is somewhat confusing in the literature, often complicated by geographical site and environmental conditions under which studies were undertaken.

Checking seems to be the most common form of weather-related deterioration of trees killed by fire. Hadfield and Magelssen (2006) observed that trees growing on the driest, hottest sites checked before those on moister, cooler sites after fires in Washington State. Lowell and Cahill (1996) also noted that trees growing on hot, dry, or windy sites in coastal northern California and southern Oregon forests were also more likely to become weather-checked after fire than those on more mesic and cooler sites.

Most weather checks occur at the top of a tree where thin bark may slough off during drying and shrinkage, and where it is more prone to exposure to the elements (Kimmey 1955; Lowell and Cahill 1996). Conversely, most sap rot occurs on the lower logs, at least in the case of beetle-killed trees (Parry et al. 1996). In addition, it has been suggested by Parry et al (1996) that the amount of checking observed in their study of beetle-killed trees may have been due to several years of drought that followed tree death, and hastened drying.

Weather checking can vary depending on the circumstances in which the fire occurs. Size and species of tree are especially important in predisposition of trees to checking. In some fire deterioration studies, weather checking was identified as an important component of deterioration (Lowell and Cahill 1996; Hadfield and Magelssen 2006); in other cases checking was not observed to be an important agent in post-fire volume loss relative to the losses caused by insects and fungi (see Beal et al. 1935; Kimmey and Furniss 1943; Kimmey 1955; Basham 1958), because it usually occurs mostly in small diameter trees and in tops where the volume loss may be negligible (Lowell et al. 1992). It is important to note that the studies where weather checking did not appear to be as important as insect- and disease-caused losses were mostly done in larger trees having thick bark, and also in moister environments than conditions typically found in eastern Washington and Oregon.

In our deterioration monitoring study, our data on weathering effects on fire-injured and fire-killed trees was limited in timing to the first two seasons after the School Fire. We found ample evidence of checking in the log decks (cf. Figs. 2, 3, 4, 7, and 12), but recorded few standing trees in which we observed checking (Table 1). Grand fir, both

dead and live, was the only species occurring on our variable-radius plots in which we observed weather checks. Weather checks occurred in relatively low proportion in live

Figure 12. Example of harvested grand fir log with deep seasoning checks, School Fire, Pomeroy Ranger District, Umatilla National Forest (May 8, 2007).

grand fir, but were observed in nearly one-quarter of the dead trees of that species (Table 1). Lowell and Cahill (1996) found weather checking to be a primary defect in their study of fire-killed trees, and indicate that it required scale deductions that affected product yield. During the first year after trees died, they found that 5 % of all logs,

mainly from the upper portion of the bole, required scale deductions for weather checks; for true firs, this represented 5 % of the mean cubic volume loss. During the second year, they found the mean cubic volume loss in logs with weather checking to be higher than for sap rot. By the third year, weather checking, and the volume loss attributed to it, was very high in Douglas-fir, ponderosa pine, and true fir. In some cases, checking was severe enough to cull many of the logs of those species in year three. However, when compared with sap rot, the cubic volume loss in year three represented a much larger proportion of the total volume loss than weather checking (Lowell and Cahill 1996; Parry et al. 1996). Weather checking primarily affects sawlog product recovery, and there is little or no impact on yield of chips or pulp.

Given the results of other studies, we anticipate that incidence of weather checking of trees on our School Fire plots will increase in the third year after the fire. In addition, we would expect to see weather checking becoming evident on Douglas-fir and ponderosa pine in the next season. Perhaps, if our dataset had represented more plots and trees on plots, we might have found weather checking to be present already in all conifer species in the second season after the fire, especially in those trees that had been killed by fire since there has been ample time for drying to occur.

Conclusions

In this study, we examined the deterioration of logs in decks, and in standing live and dead conifers in the second season after the August 2005 School Fire in southeastern Washington State. Our interest was in determining the incidence and depth of sap rot in these trees, and whether differences exist in sap rot conditions between live and dead trees two years after the fire occurred.

Other factors besides sap rot can cause deterioration and volume loss in trees after wildfire. These factors affect the volume of sound merchantable wood that can be recovered in salvage. These include degrade or defects attributable to insects, fungal-caused staining, checking, losses from breakage in felling, and heart-wood decay, in addition to sap rot. We briefly touched on some of these in this study, whereas other studies have provided more extensive evaluation of the agents responsible for post-fire deterioration and volume losses (cf. Beal et al. 1935; Kimmey and Furniss 1943; Kimmey 1955; Basham 1957, 1958; Lowell et at. 1992; Lowell and Cahill 1996; Hadfield and Magelssen 2006). Direct sapwood volume losses due to charring during the fire are yet another factor that affects the amount of merchantable wood recoverable from trees after a fire but we did not address those losses in this study.

Indicators of insect infestation such as woodpecker foraging, presence of pitch masses, and boring dust or frass; or other indicators of fungal invasion such as sapwood staining and pouch fungus conks are correlated with presence of sap rot, and may be useful in determining the post-fire survival of injured trees. Although, from a practical standpoint, these indicators are commonly used by entomologists and pathologists to identify potentially “dying” trees, it should be emphasized that we did not correlate these

indicators with actual tree death. Hence, they should be used cautiously, and will be most reliable when used with other methods to assess tree survival.

Defects and degrades that result from insect attacks, blue stain, sap rot, and weather checking begin almost immediately after fire occurrence. If the timing of the fire corresponds with flight of either bark beetles or woodborers, attacks will likely occur soon after the fire, initiating the deterioration process the same year as fire occurrence. Typically, these insect attacks will increase substantially in the spring and summer seasons following the fire. Initial wood fiber volume losses in individual trees may be low for the first year or two, but these losses increase over time.

Our study found that there is significant variation in sap rot penetration depth between grand firs that are live and dead, but not among cardinal sampling locations within live or dead trees, two seasons after the fire. We found similar results for live and dead Douglas-firs. From our data we could not determine to what extent this pattern also occurs in ponderosa pine, western larch, or other conifer species, but we expect that it does. Our study was limited in scope and sample size due to the short time available to obtain sample data. Moreover, we conducted this study only during the second season, approximately 21 months after the fire; hence, we captured only the beginning of deterioration of fire-injured or fire-killed trees that occurred on the School Fire. Sampling at a later date, or over a longer period of time, as was done by authors of other studies cited here, likely would have more clearly shown trends and differences among conifers.

Finally, out of concern for the biological implications contained in this study, as well as other published studies cited above, we comment on the February 12, 2007 opinion rendered by the 9th Circuit Court of Appeals in the case of the School Fire Salvage Recovery Project. The logging of any "live" tree $\geq$ 21 inches in diameter at breast-height (dbh), as prohibited by the Forest Plan (Eastside Wildlife Screens) is the issue that is at the heart of the 9th Circuit Court of Appeals opinion. Specifically, the Appeals Court reasoned that since the Forest Service had not adopted a technical definition of "live trees" for this project, in the Court's opinion the dictionary definition of "live," meaning "to be alive" or "not dead," should be applied in this case (USDA 2007). Moreover, the Appeals Court added that "dying" trees implied that the trees are not yet "dead"; hence, they could not be harvested, either. Given that "dying" trees that meet certain physiological criteria (e.g., damaged or attacked by pests and expected to have a dead or nonfunctional root system or a nonfunctional stem within 5 years) may be considered either dead or in imminent danger of death (Filip et al. 2007), and that post-fire deterioration is progressive over time, eventually leading to tree death—the cessation of all life processes—we submit that the Appeal Court's prohibition against salvaging "dying" trees because they are not yet "dead" is biologically flawed, and does not reflect the current science documented in the peer-reviewed literature (see Filip et al. 2007 for a complete discussion). From an operational and economical standpoint it is prudent to salvage those trees expected to undergo delayed mortality before advanced deterioration renders them useless for lumber product manufacture. Hence, we support the more

biologically-, operationally-, and economically-sound definition of a "dead" tree as described in the paper by Filip et al. (2007).

We believe the message from the post-fire deterioration literature and our study results is clear: deterioration of sound wood begins almost immediately after a fire kills or injures trees, and increases progressively over time, adding to merchantable volume losses with each delay of salvage until eventually deterioration has rendered fire-killed timber virtually worthless economically. Accordingly, from an economic standpoint, we recommend the salvage of fire-injured trees of all merchantable sizes that have poor chance of survival when determined by sound, science-based procedures to assess post-fire tree survival like those given by Scott et al. (2002), and as amended by Scott et al. (2003) and Scott and Schmitt (2006). It would be desirable from an economic standpoint to begin salvaging as soon as possible and be able to conclude salvaging within 12 months after the fire to minimize wood volume losses from deterioration and maximize recovery of sound wood volume. However, this recommendation must be tempered when evaluation of environmental conditions suggest salvage logging would be unwise under the circumstances. In some situations, it may be economically infeasible to adequately protect resources and mitigate undesirable effects, or environmentally imprudent to proceed, such as when too few trees are available for salvage to maintain adequate levels or distributions of wildlife snags, or because of the presence of fragile, steep slopes, shallow soils, or a host of other factors that would argue against salvage logging.

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